

Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Huleia NWR

Prepared For

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat “migration” as salt marshes transgress landward and replace tidal freshwater and brackish marsh (Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 1 refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al., 1991; Lee, J.K., R.A. Park, and P.W. Mause. 1992; Park, R.A., J.K. Lee, and D. Canning 1993; Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002; National Wildlife Federation et al., 2006; Glick, Clough, et al. 2007; Craft et al., 2009).

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site-specific data.
- **Overwash:** Barrier islands of under 500 meters width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain or can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- **Accretion Feedback Component:** Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback will be used in USFWS simulations, but only where adequate data exist for parameterization.
- **Salinity Model:** Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- **Integrated Elevation Analysis:** SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- **Flexible Elevation Ranges for land categories:** If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough, Park, Fuller, 2010). This document is available at <http://warrenpinnacle.com/prof/SLAMM>

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (CREM 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

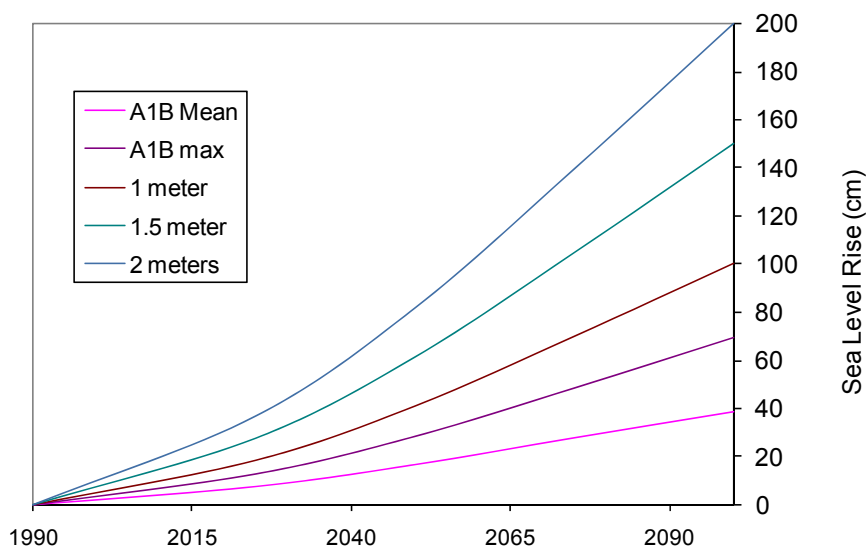
SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC, 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 “excluding future rapid dynamical changes in ice flow.” The A1B-mean scenario

that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 meters of global sea level rise by 2100. A1B-maximum predicts 0.69 meters of global SLR by 2100.

The latest literature (Chen et al., 2006, Monaghan et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf, 2007) suggests that, taking into account possible model error, a feasible range by 2100 of 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf, 2009). Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008) A recent paper by Grinsted et. al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario..." Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters, and 2 meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

The digital elevation map used in this simulation was supplied by FEMA based on high-resolution LiDAR with a 2006 photo date (Figure 2).

The wetlands layer for the study area was produced by the National Wetlands Inventory and is based on a 2005 photo date.

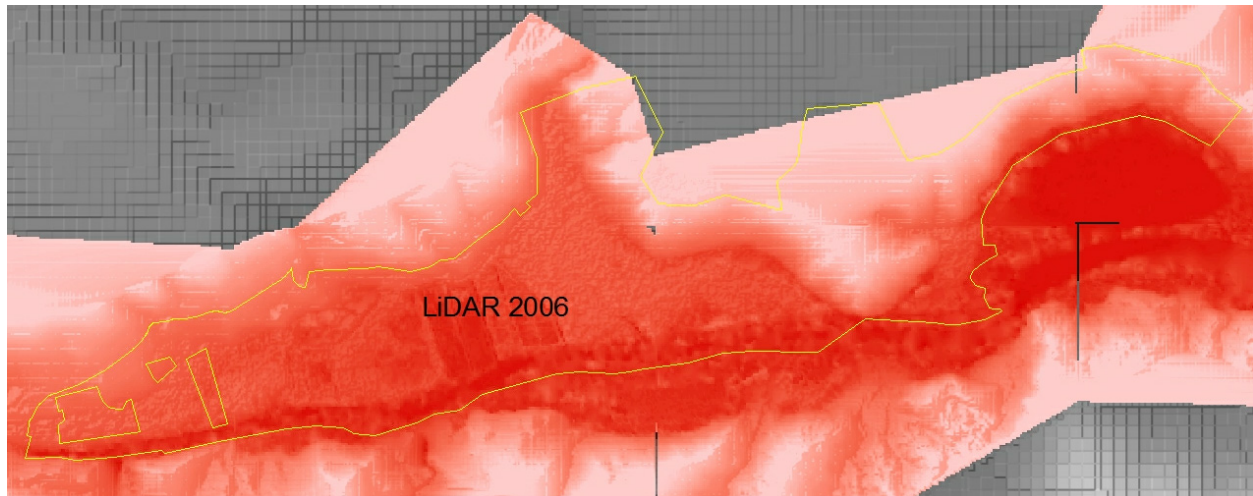


Figure 1: DEM source map for Huleia NWR (thin yellow boundary). Red is LiDAR and grey is NED (National Elevation Dataset).

Converting the NWI survey into 15 meter cells indicates that the approximately two hundred forty one acre refuge (approved acquisition boundary including water) is composed of primarily the following categories:

Undeveloped Dry Land	60.2%
Saltmarsh	17.7%
Tidal Fresh Marsh	8.1%
Mangrove	5.9%
Estuarine Open Water	2.9%
Developed Dry Land	1.4%
Trans. Salt Marsh	1.2%

According to the National Wetland Inventory, Huleia NWR has one impounded region consisting of regularly flooded and tidal fresh marsh (Figure 3). A pool of impounded estuarine water lies just outside the refuge boundary.

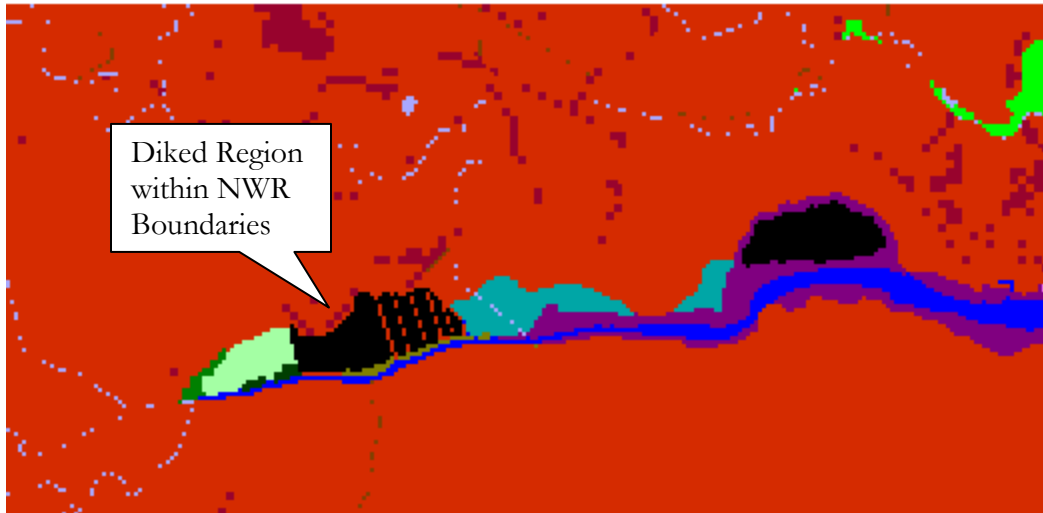


Figure 2: Diked areas in black.

The historic trend for sea level rise was estimated at 1.53 mm/year using the nearest NOAA gage with SLR data (1612340, Honolulu, HI). The rate of sea level rise for this refuge is slightly lower than the global average for the last 100 years (approximately 1.7 mm/year).

The tide range was estimated at 0.46 meters (great diurnal range or GT) using a report on Huleia NWR tidal fluctuations performed between 2008 and 2009 (2009 unpublished “Technical Memorandum on Huleia NWR Tidal Fluctuations” by Fred Wurster). This value is slightly less than that measured at the nearest downriver NOAA gage (0.56 meters at Nawiliwili, HI).

No local accretion or erosion data were available for this study area. Instead, the model used default accretion rates, with regularly flooded values of 3.9 mm/year and fresh marsh accretion values of 5.9 mm/year. Marsh erosion is not predicted to be significant in this area due to insufficient wave setup.

The vertical datum of the elevation data for this region is Mean Sea Level (MSL). Therefore, the model parameterization requires an “MTL – MSL” correction for this simulation. The value of -0.005 was chosen based on the nearest NOAA gage (1611400; Nawiliwili, HI).

Modeled U.S. Fish and Wildlife Service refuge boundaries for Hawaii are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis was 15 meter by 15 meter cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

Carl Berg, the Deputy Refuge Manager at the Kauai NWR Complex, indicated that the tidal influence at the refuge is slightly different than at the nearest NOAA gage (1611400; Nawiliwili, HI). Mr. Berg also provided us with the report that was used to modify the tidal influence for this refuge. (2009 Wurster, as documented above)

SUMMARY OF SLAMM INPUT PARAMETERS FOR HULEIA NWR

Parameter	Global
Description	Huleia
NWI Photo Date (YYYY)	2003
DEM Date (YYYY)	2006
Direction Offshore [n,s,e,w]	South
Historic Trend (mm/yr)	1.53
"MTL- MSL " (m)	-0.005
GT Great Diurnal Tide Range (m)	0.46
Salt Elev. (m above MTL)	0.39
Marsh Erosion (horz. m /yr)	1.8
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	2
Reg. Flood Marsh Accr (mm/yr)	3.9
Irreg. Flood Marsh Accr (mm/yr)	4.7
Tidal Fresh Marsh Accr (mm/yr)	5.9
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	15
Use Elev Pre-processor [True,False]	FALSE

Results

Huleia NWR is predicted to be resilient to the effects of sea level rise (SLR). Refuge dry land – which makes up roughly 60% of the refuge – is predicted to lose 13% of its initial land coverage in the most extreme SLR scenario. Regularly flooded (salt) marsh and tidal fresh marsh are both predicted to be much more resilient.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Undeveloped Dry Land	4%	6%	8%	10%	13%
Saltmarsh	0%	0%	0%	2%	8%
Tidal Fresh Marsh	0%	0%	0%	0%	6%
Trans. Salt Marsh	-2%	0%	25%	32%	75%

Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

Maps of SLAMM input and output to follow will use the following legend:



Huleia Raster

IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Undeveloped Dry Land	145.2	143.1	142.6	141.2	139.4
Saltmarsh	42.6	42.6	42.6	42.6	42.6
Tidal Fresh Marsh	19.5	19.5	19.5	19.5	19.5
Mangrove	14.2	16.2	16.7	18.1	19.8
Estuarine Open Water	6.9	7.1	7.2	7.2	7.6
Developed Dry Land	3.3	3.3	3.3	3.3	3.3
Trans. Salt Marsh	2.8	2.8	2.8	2.8	2.9
Riverine Tidal	2.1	1.9	1.8	1.8	1.5
Swamp	1.6	1.6	1.6	1.6	1.6
Tidal Swamp	1.6	1.6	1.6	1.6	1.6
Inland Open Water	1.0	1.0	1.0	1.0	1.0
Inland Shore	0.4	0.4	0.4	0.4	0.4
Total (incl. water)	241.2	241.2	241.2	241.2	241.2



Huleia NWR, Initial Condition



Huleia NWR, 2025, Scenario A1B Mean



Huleia NWR, 2050, Scenario A1B Mean



Huleia NWR, 2075, Scenario A1B Mean



Huleia NWR, 2100, Scenario A1B Mean

Huleia Raster

IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Undeveloped Dry Land	145.2	142.9	141.1	138.2	136.2
Saltmarsh	42.6	42.6	42.6	42.6	42.5
Tidal Fresh Marsh	19.5	19.5	19.5	19.5	19.5
Mangrove	14.2	16.4	18.2	20.9	23.0
Estuarine Open Water	6.9	7.2	7.3	7.6	8.7
Developed Dry Land	3.3	3.3	3.3	3.3	3.3
Trans. Salt Marsh	2.8	2.8	2.8	2.9	2.8
Riverine Tidal	2.1	1.8	1.8	1.4	0.7
Swamp	1.6	1.6	1.6	1.6	1.6
Tidal Swamp	1.6	1.6	1.6	1.6	1.6
Inland Open Water	1.0	1.0	1.0	1.0	0.8
Inland Shore	0.4	0.4	0.4	0.4	0.3
Total (incl. water)	241.2	241.2	241.2	241.2	241.2



Huleia NWR, Initial Condition



Huleia NWR, 2025, Scenario A1B Maximum



Huleia NWR, 2050, Scenario A1B Maximum



Huleia NWR, 2075, Scenario A1B Maximum



Huleia NWR, 2100, Scenario A1B Maximum

Huleia Raster

1 Meter Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Undeveloped Dry Land	145.2	142.6	139.4	136.3	134.2
Saltmarsh	42.6	42.6	42.6	42.5	42.4
Tidal Fresh Marsh	19.5	19.5	19.5	19.5	19.5
Mangrove	14.2	16.7	19.8	22.8	23.2
Estuarine Open Water	6.9	7.2	7.4	9.0	11.6
Developed Dry Land	3.3	3.3	3.3	3.3	3.3
Trans. Salt Marsh	2.8	2.8	2.9	2.6	2.1
Riverine Tidal	2.1	1.8	1.7	0.7	0.5
Swamp	1.6	1.6	1.6	1.6	1.6
Tidal Swamp	1.6	1.6	1.6	1.6	1.5
Inland Open Water	1.0	1.0	1.0	0.8	0.7
Inland Shore	0.4	0.4	0.4	0.3	0.3
Tidal Flat	0.0	0.0	0.0	0.0	0.1
Total (incl. water)	241.2	241.2	241.2	241.2	241.2



Huleia NWR, Initial Condition



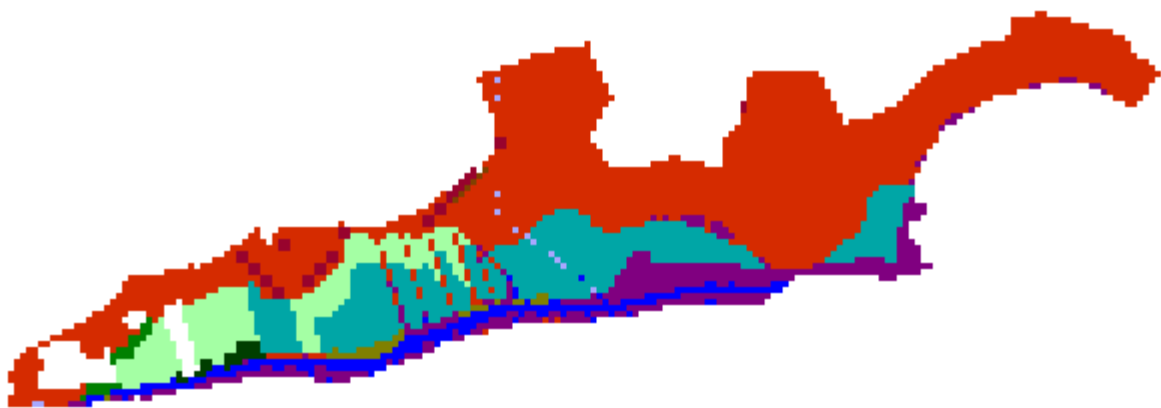
Huleia NWR, 2025, 1 meter



Huleia NWR, 2050, 1 meter



Huleia NWR, 2075, 1 meter



Huleia NWR, 2100, 1 meter

Huleia Raster

1.5 Meters Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Undeveloped Dry Land	145.2	141.8	137.5	134.1	131.1
Saltmarsh	42.6	42.6	42.5	42.3	41.6
Tidal Fresh Marsh	19.5	19.5	19.5	19.5	19.5
Mangrove	14.2	17.5	21.5	19.6	15.8
Estuarine Open Water	6.9	7.3	8.1	15.6	23.5
Developed Dry Land	3.3	3.3	3.3	3.3	3.3
Trans. Salt Marsh	2.8	2.8	2.6	2.0	1.9
Riverine Tidal	2.1	1.8	1.5	0.4	0.1
Swamp	1.6	1.6	1.6	1.6	1.5
Tidal Swamp	1.6	1.6	1.6	1.5	1.2
Inland Open Water	1.0	1.0	1.0	0.7	0.7
Inland Shore	0.4	0.4	0.3	0.3	0.3
Tidal Flat	0.0	0.0	0.0	0.1	0.7
Total (incl. water)	241.2	241.2	241.2	241.2	241.2



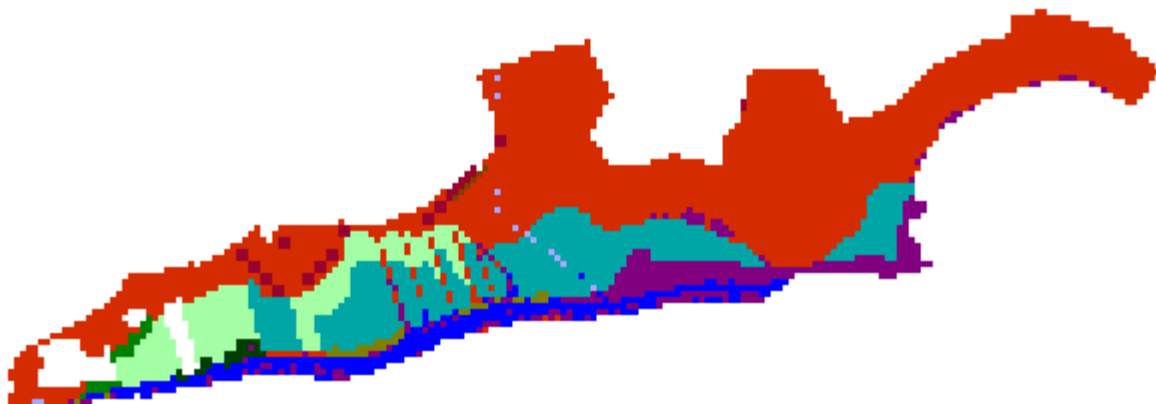
Huleia NWR, Initial Condition



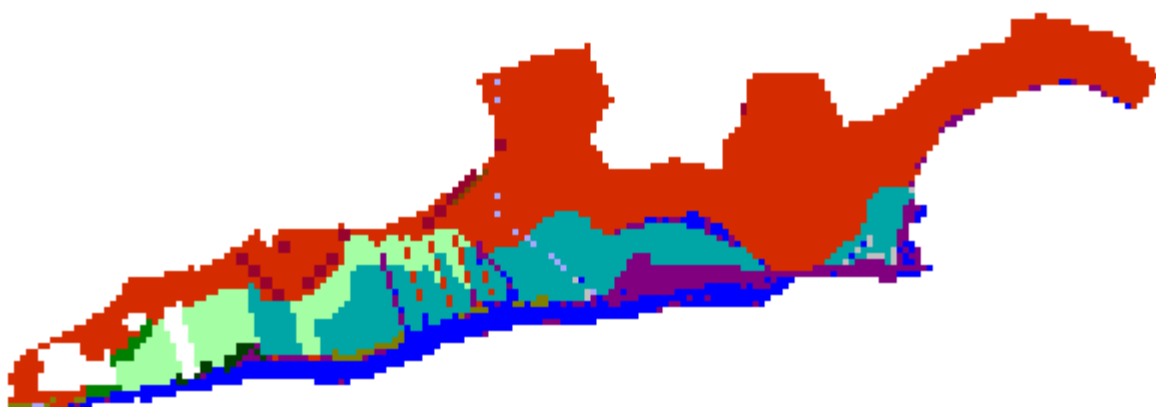
Huleia NWR, 2025, 1.5 meter



Huleia NWR, 2050, 1.5 meter



Huleia NWR, 2075, 1.5 meter



Huleia NWR, 2100, 1.5 meter

Huleia Raster

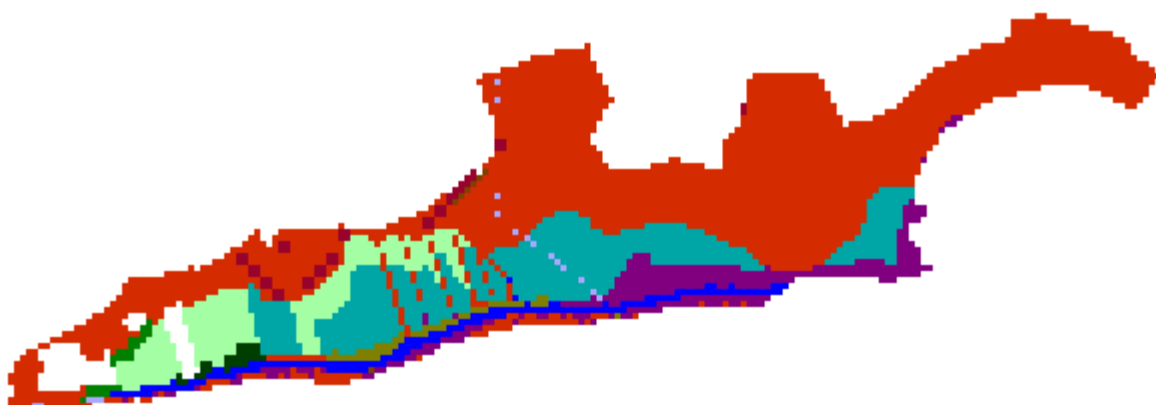
2 Meters Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Undeveloped Dry Land	145.2	140.9	135.8	131.6	126.9
Saltmarsh	42.6	42.6	42.4	41.7	39.1
Tidal Fresh Marsh	19.5	19.5	19.5	19.5	18.4
Mangrove	14.2	18.4	21.0	15.7	14.2
Estuarine Open Water	6.9	7.3	11.3	22.7	33.4
Developed Dry Land	3.3	3.3	3.3	3.3	3.3
Trans. Salt Marsh	2.8	2.8	2.3	2.0	0.7
Riverine Tidal	2.1	1.8	0.9	0.1	0.0
Swamp	1.6	1.6	1.6	1.6	1.4
Tidal Swamp	1.6	1.6	1.6	1.3	0.5
Inland Open Water	1.0	1.0	1.0	0.7	0.3
Inland Shore	0.4	0.4	0.3	0.3	0.3
Tidal Flat	0.0	0.0	0.1	0.7	2.5
Total (incl. water)	241.2	241.2	241.2	241.2	241.2



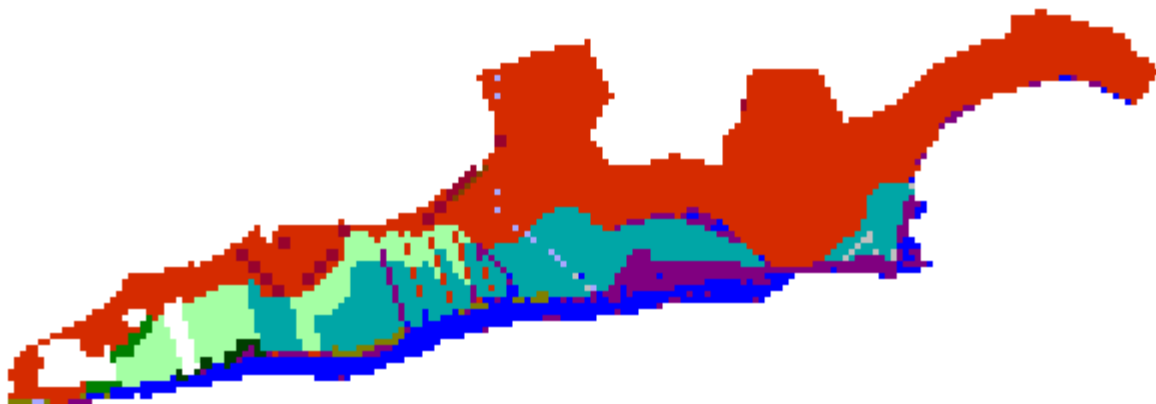
Huleia NWR, Initial Condition



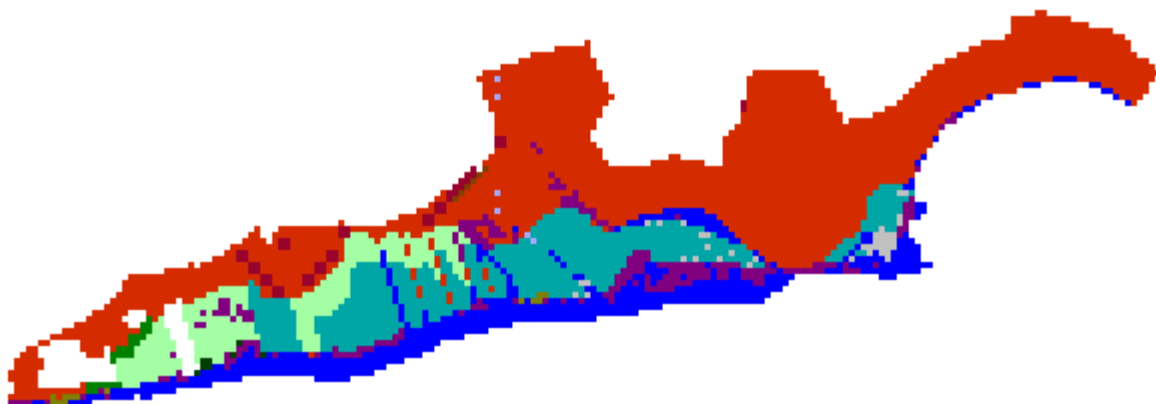
Huleia NWR, 2025, 2 meters



Huleia NWR, 2050, 2 meters



Huleia NWR, 2075, 2 meters



Huleia NWR, 2100, 2 meters

Discussion

Huleia NWR is several kilometers up river from the Nawiliwili tide gage, leading to reduced tide levels in the refuge. The majority of the refuge is composed of high elevation dry land which lies outside of tidal influence.

Elevation data for this site are subject to additional uncertainty as there is no manner of adjusting elevation data to the site-specific mean tide level. (Moving up river, mean-tide levels tend to become higher when referenced to a fixed vertical datum due to the presence of fresh water.) Lacking such information, data for this site were adjusted to match the mean tide level at the Nawiliwili gage. Moving elevations downward, however, resulted in predictions of significant dry-land loss south of the refuge. This suggests that the difference between mean tide level at this site and at Nawiliwili is minor.

Based on these elevation data, the majority of the “regularly flooded” marshes are located above tidal influence, a characteristic that suggests some uncertainty as to the actual wetland type. Contact with refuge employees indicated that this land (Figure 4) is full of freshwater wetland plant species, but likely does receive regular tidal inundation. This could suggest that a “tidal-fresh” designation would be more appropriate for the location in question.

However, such high wetland elevations produce a significant resilience to the effects of sea level rise. This is because the lower-elevation boundary for these marshes (the mean tide level) remains far below the initial-condition elevations for these marshes. Despite the predicted resilience of these marshes to loss, the extent of salinity will likely change under higher rates of sea level rise as the marshes become more frequently inundated with salt water.

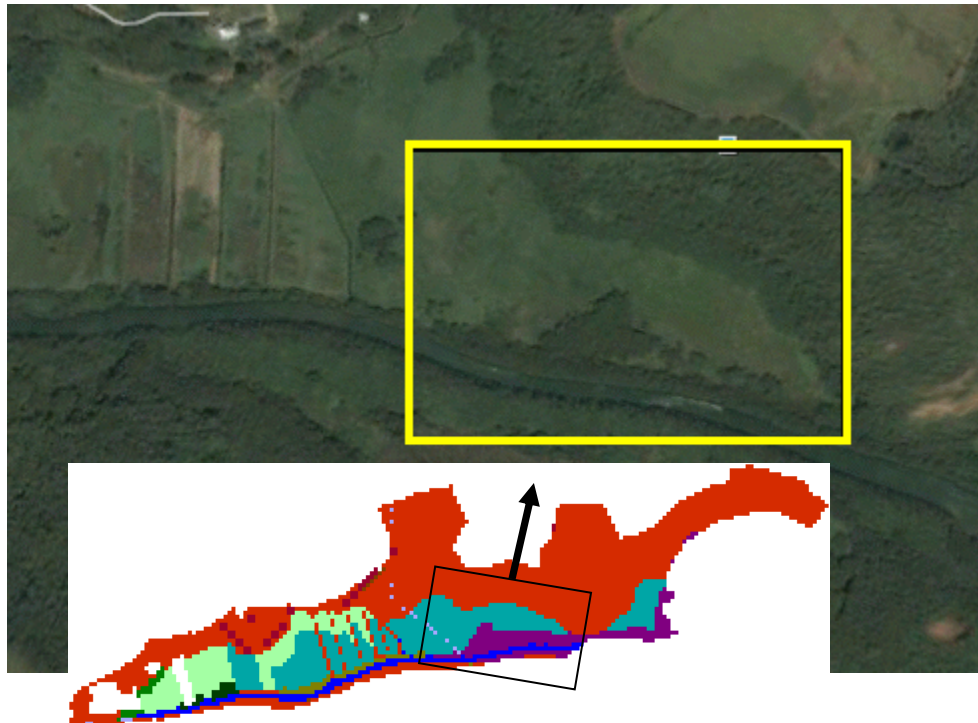


Figure 3: Area of regularly flooded marsh with elevations that suggest significant resilience to inundation.

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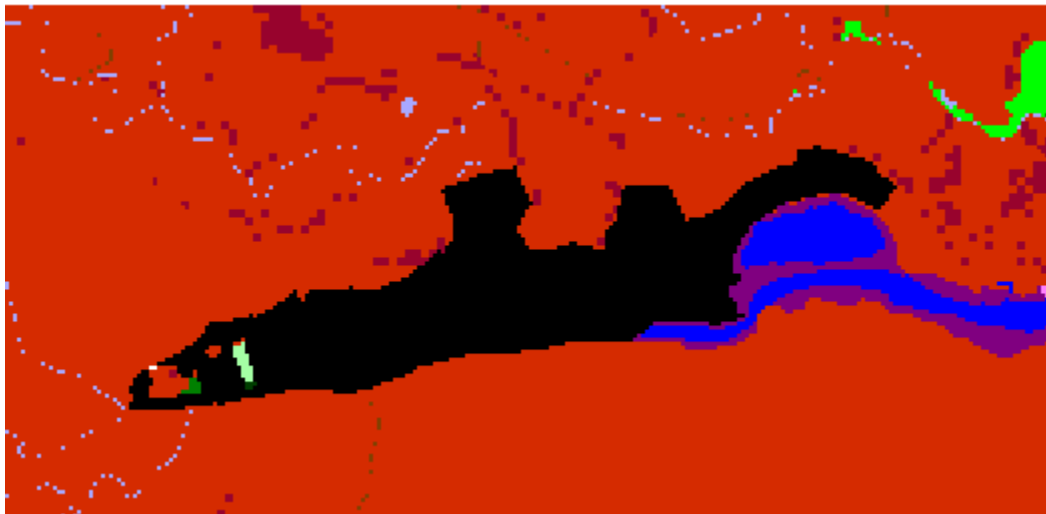
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Appendix A: Contextual Results

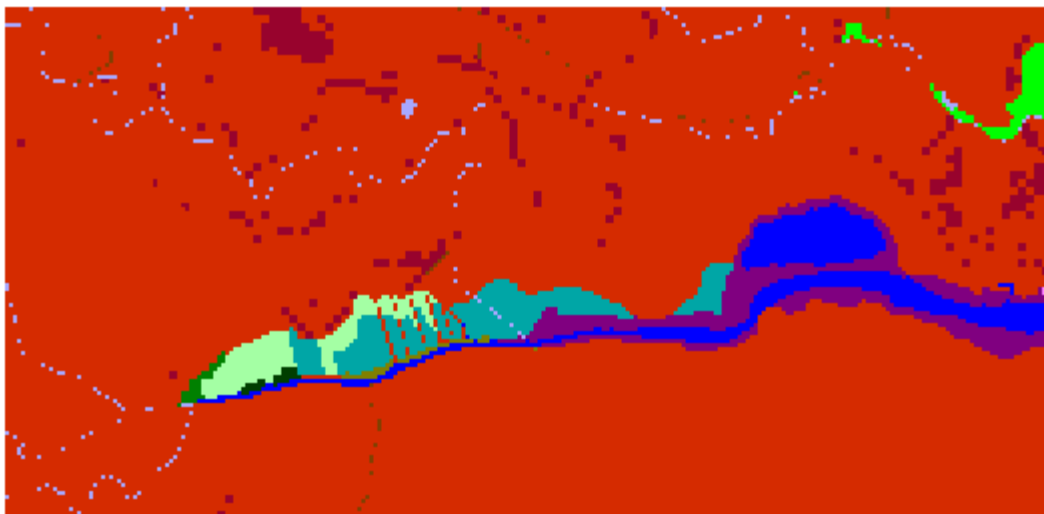
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean.

For this reason, an area larger than the boundaries of the USFWS refuge was modeled. These results maps are presented here with the following caveats:

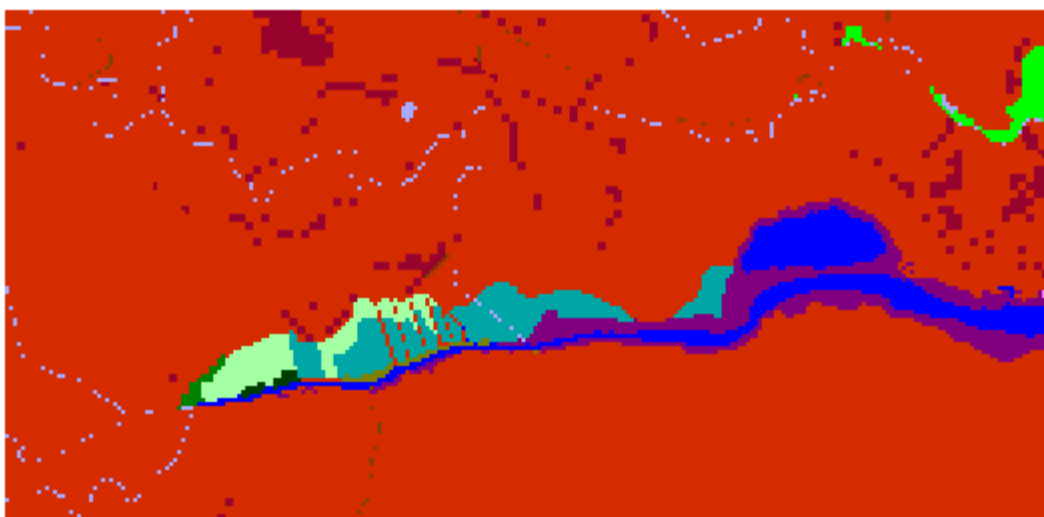
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to assess the probable location and effects of dikes for USFWS refuges, but this effort was not made for surrounding areas.



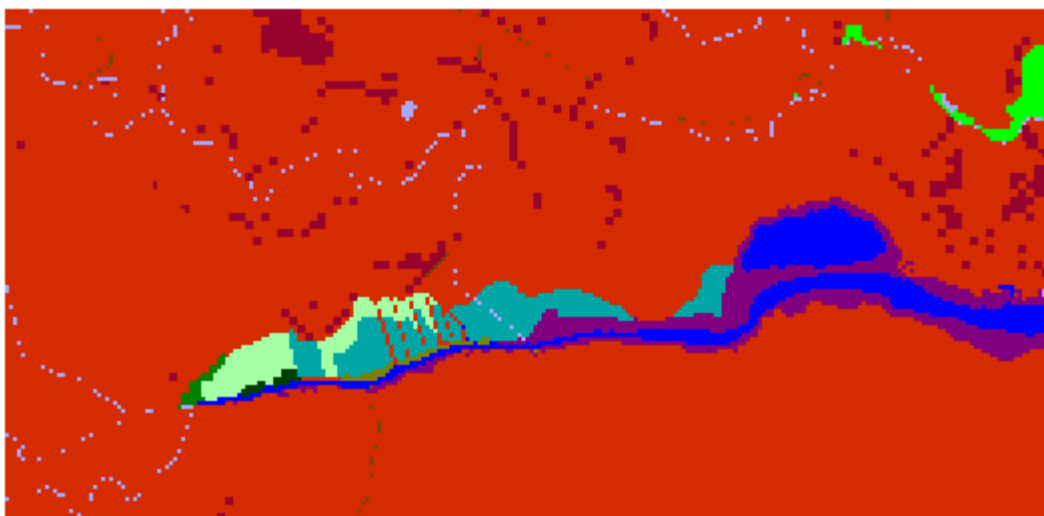
Huleia National Wildlife Refuge within simulation context (black).



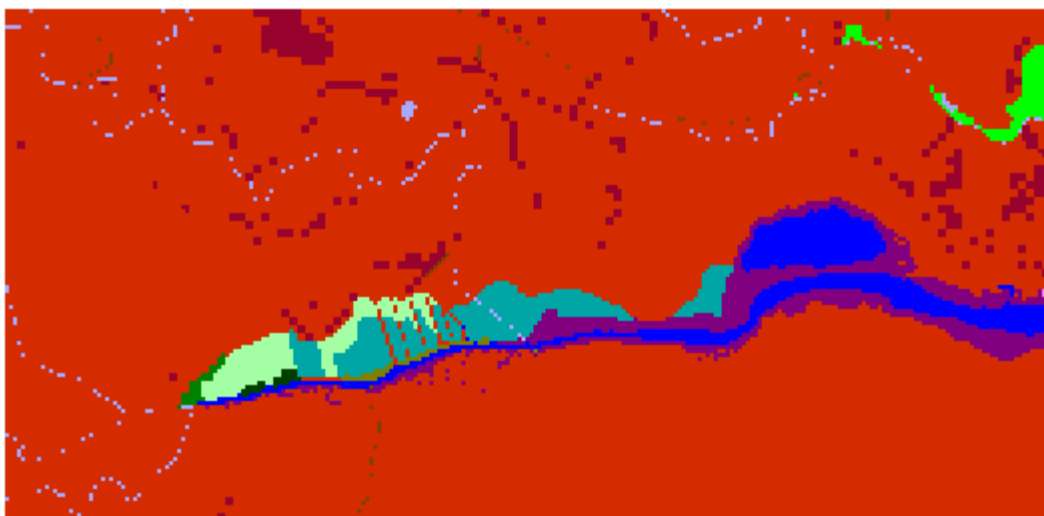
Huleia Context, Initial Condition



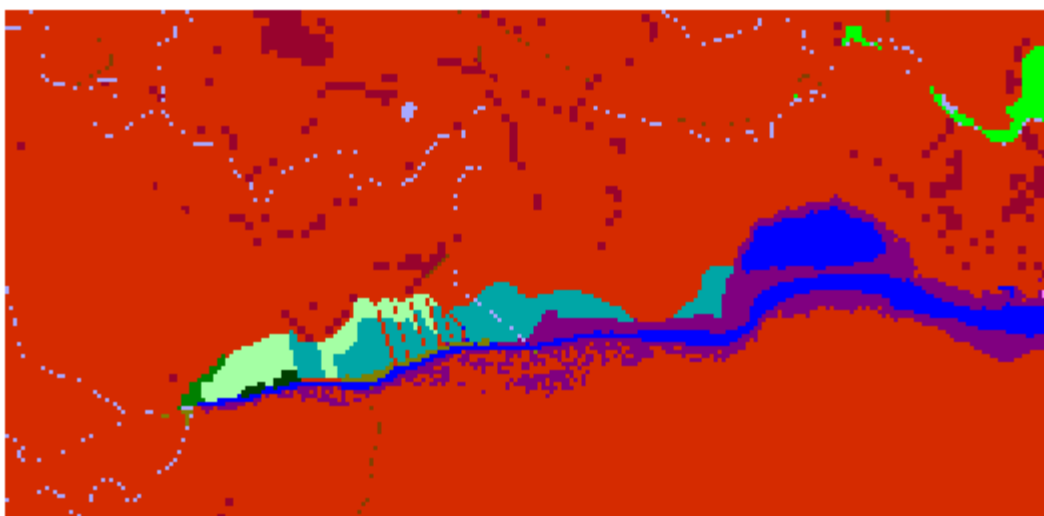
Huleia Context, 2025, Scenario A1B Mean



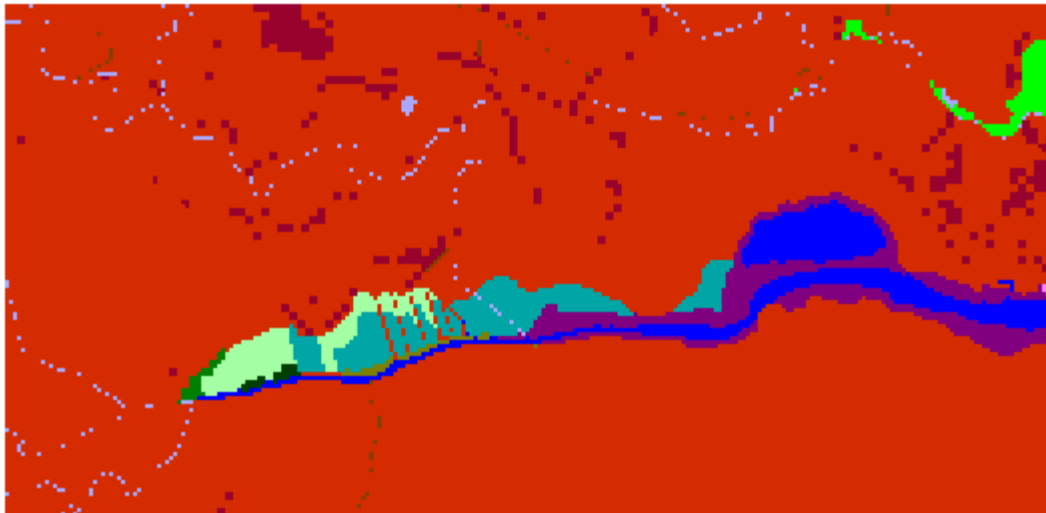
Huleia Context, 2050, Scenario A1B Mean



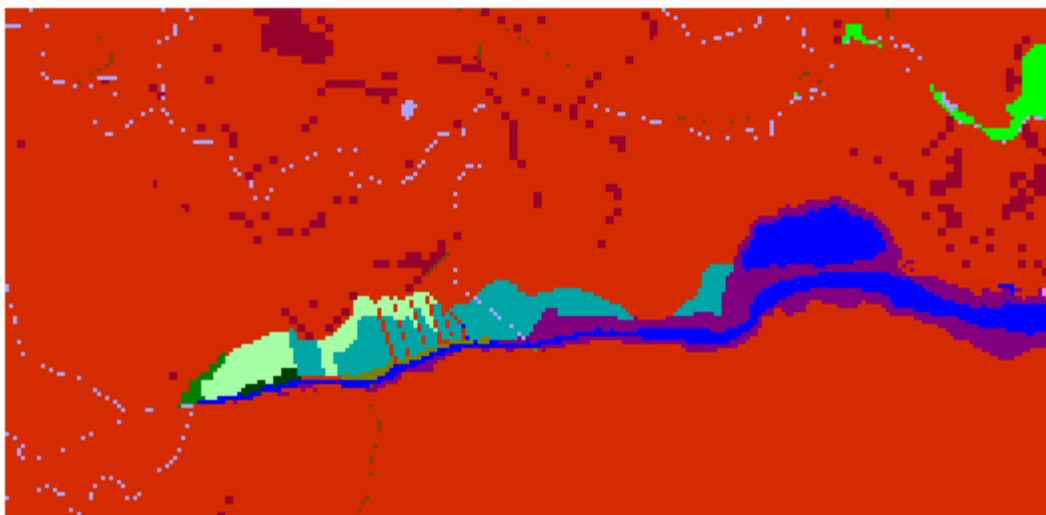
Huleia Context, 2075, Scenario A1B Mean



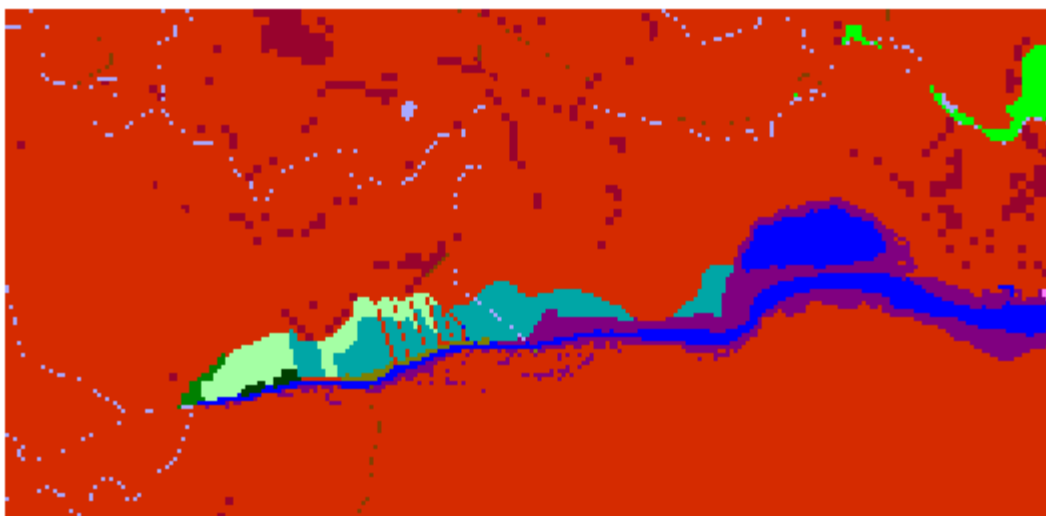
Huleia Context, 2100, Scenario A1B Mean



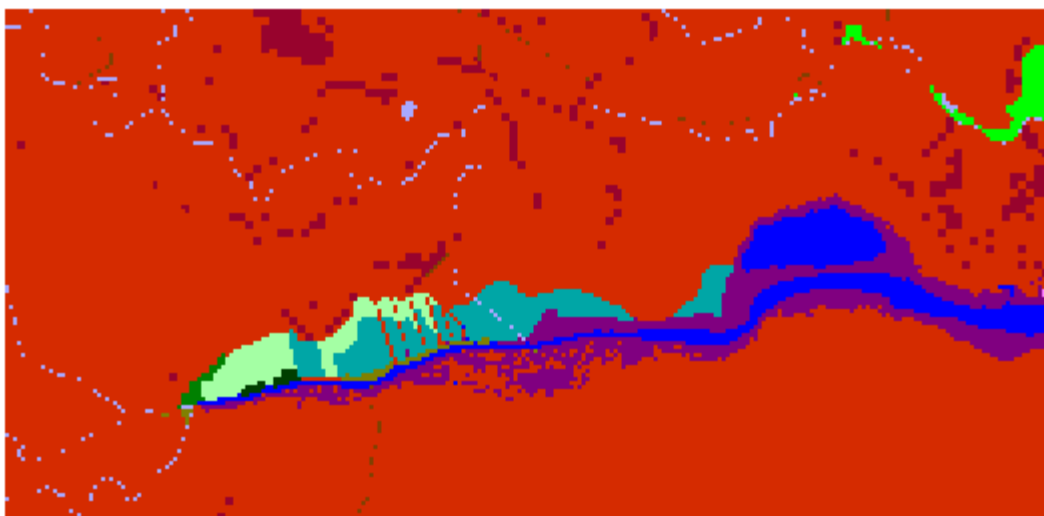
Huleia Context, Initial Condition



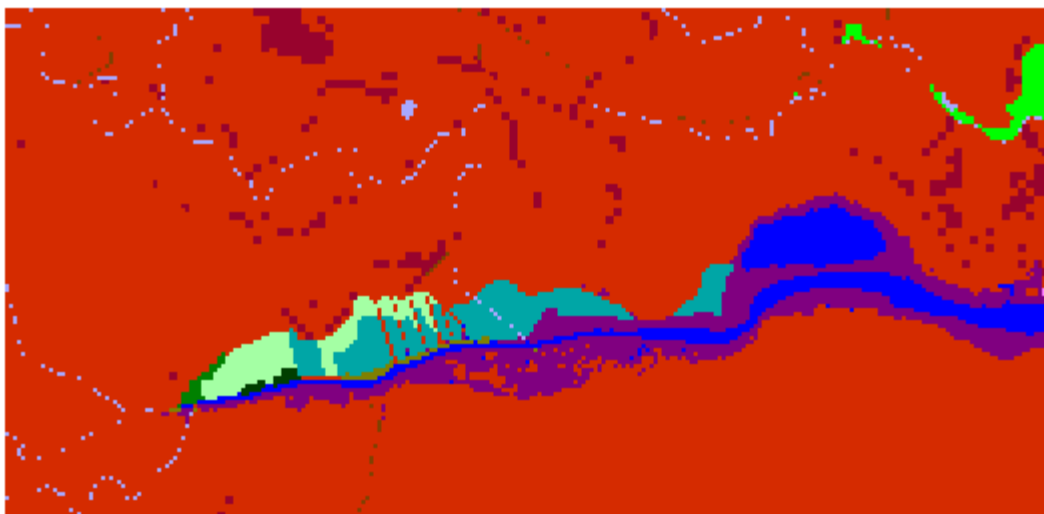
Huleia Context, 2025, Scenario A1B Maximum



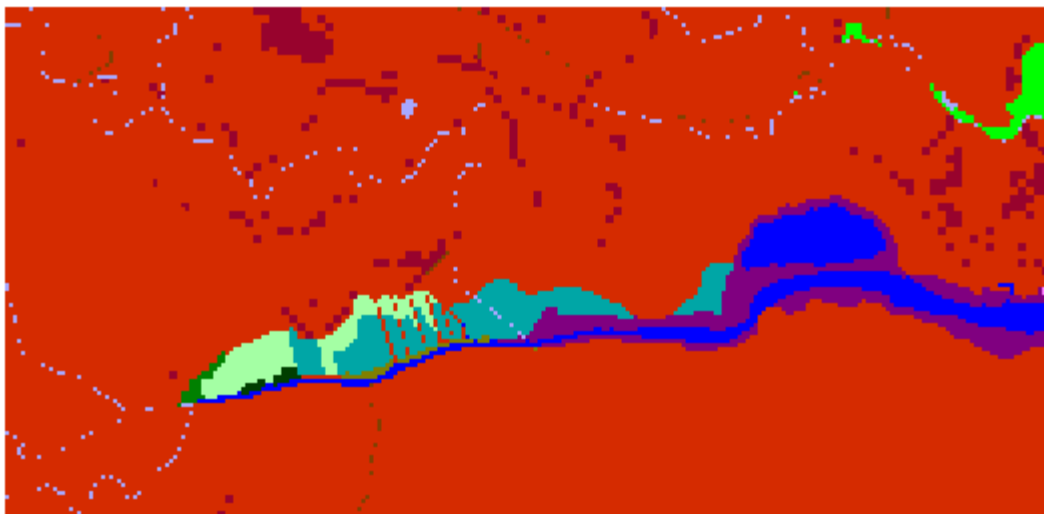
Huleia Context, 2050, Scenario A1B Maximum



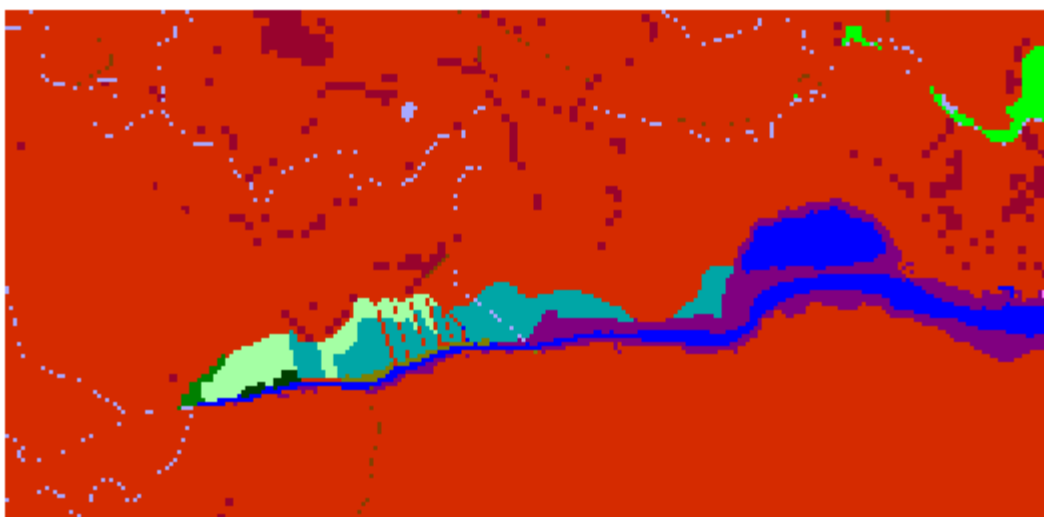
Huleia Context, 2075, Scenario A1B Maximum



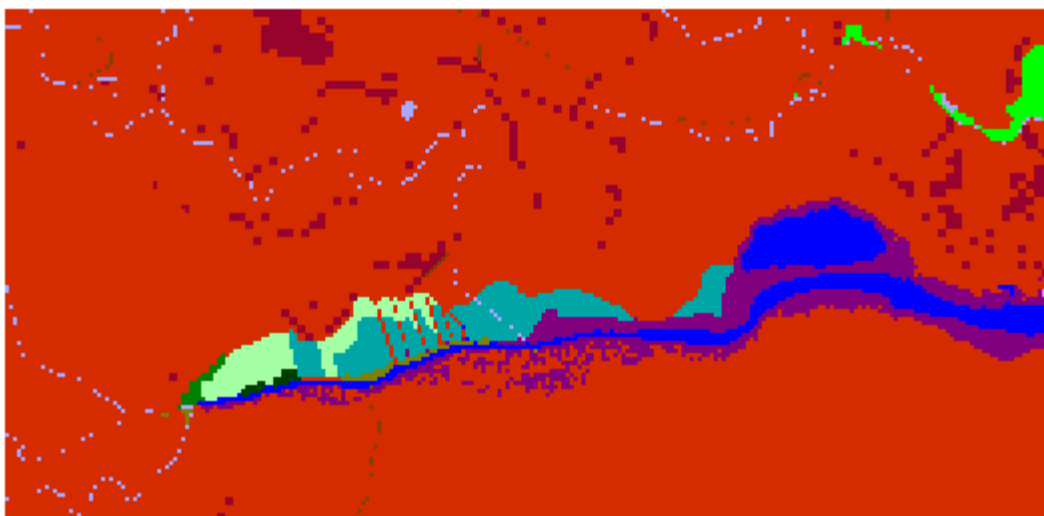
Huleia Context, 2100, Scenario A1B Maximum



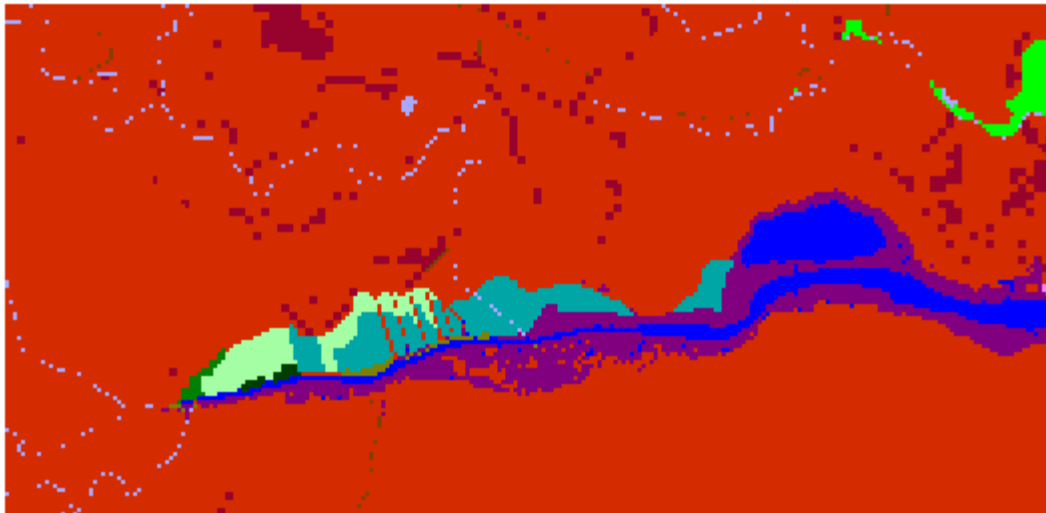
Huleia Context, Initial Condition



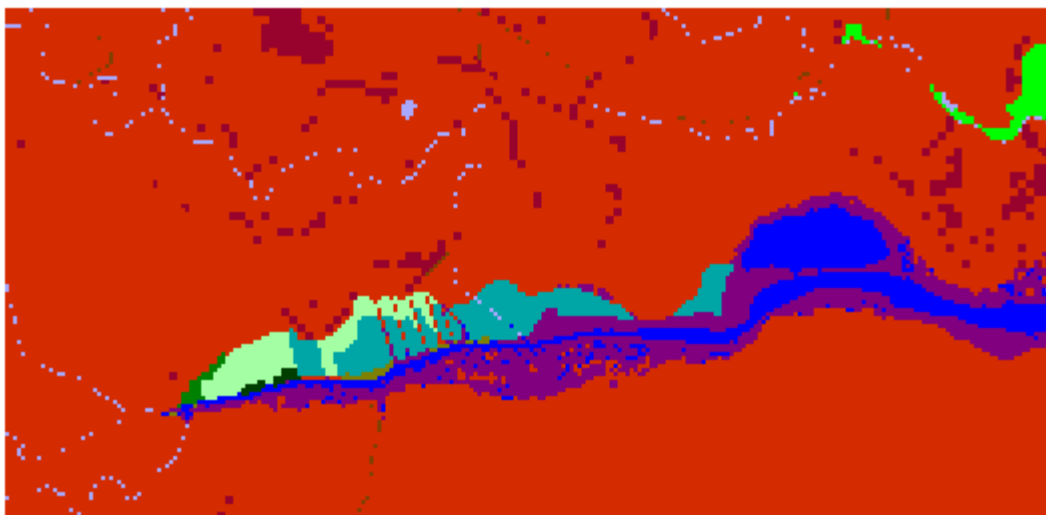
Huleia Context, 2025, 1 meter



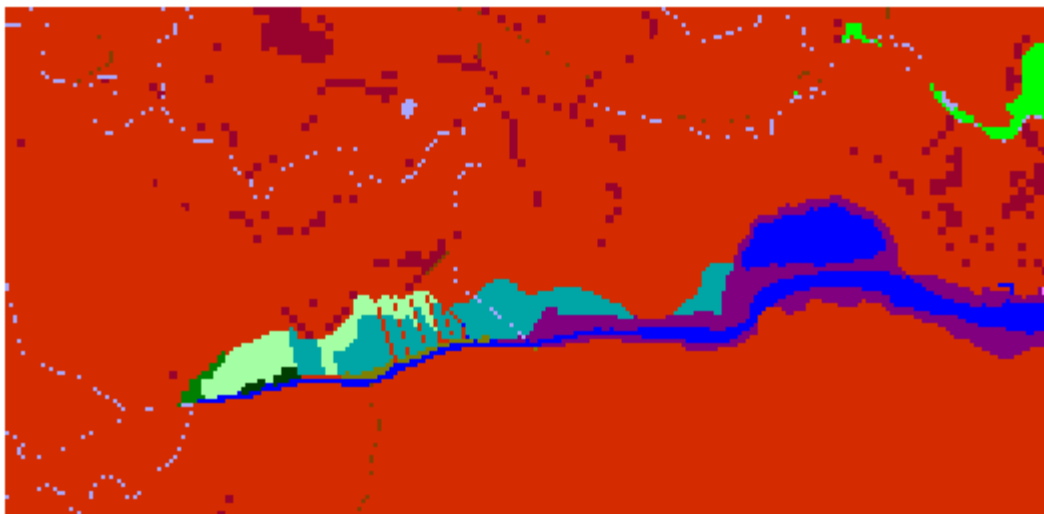
Huleia Context, 2050, 1 meter



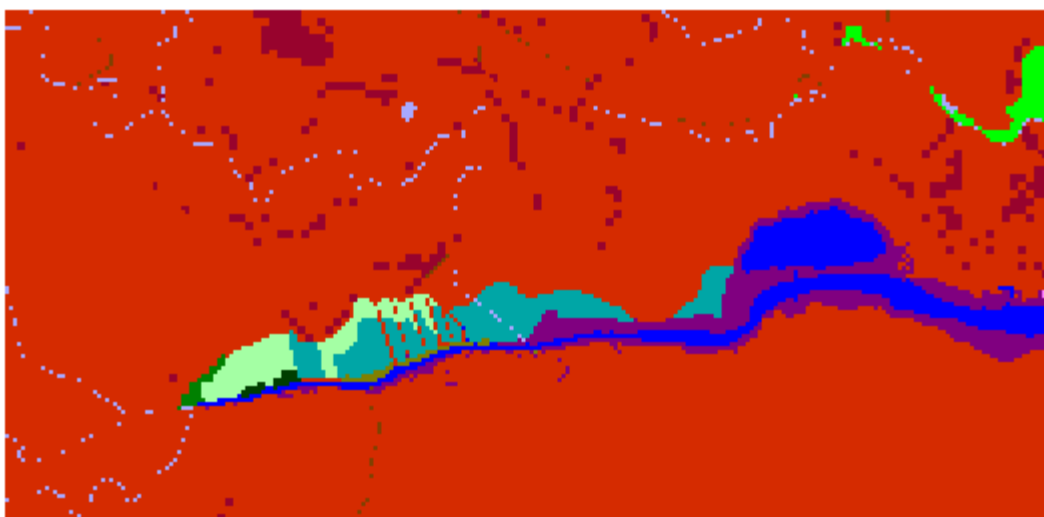
Huleia Context, 2075, 1 meter



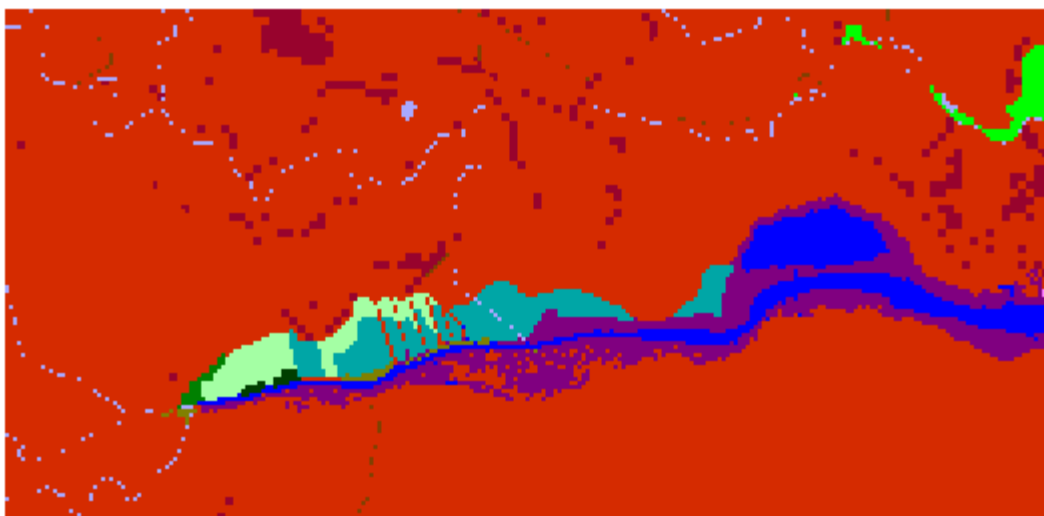
Huleia Context, 2100, 1 meter



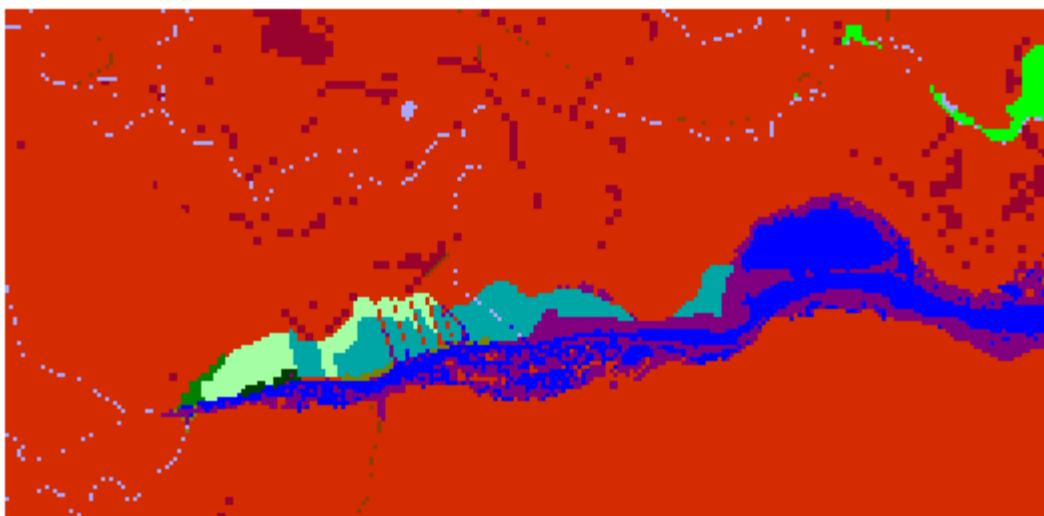
Huleia Context, Initial Condition



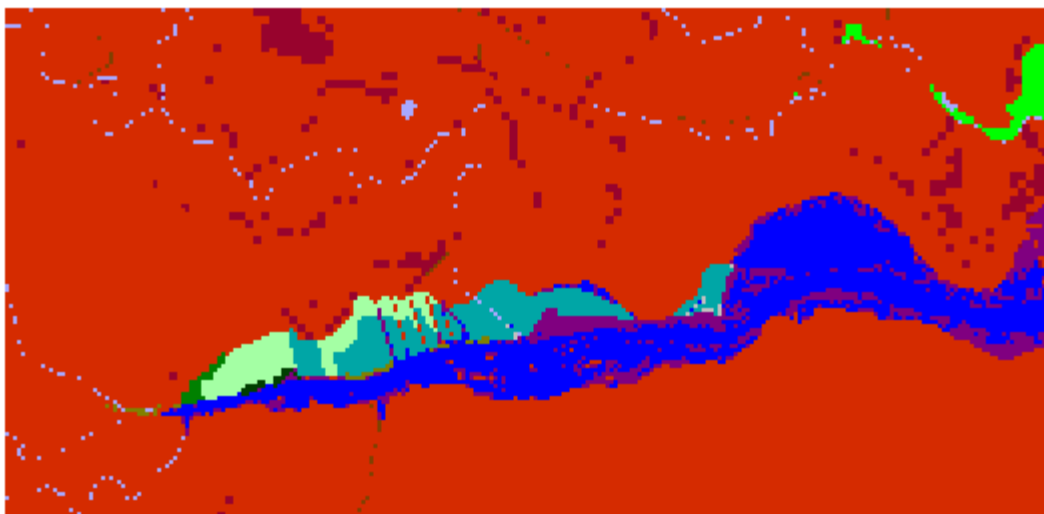
Huleia Context, 2025, 1.5 meter



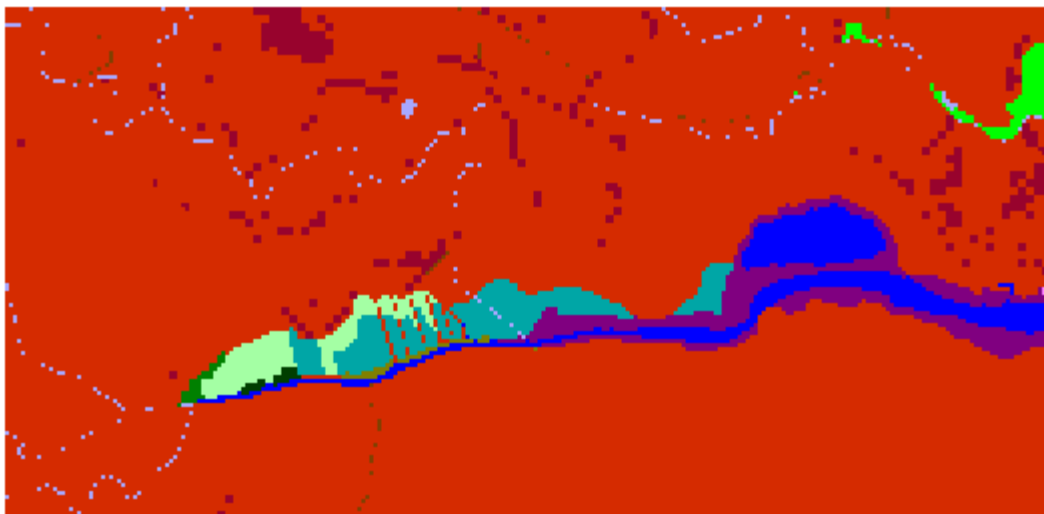
Huleia Context, 2050, 1.5 meter



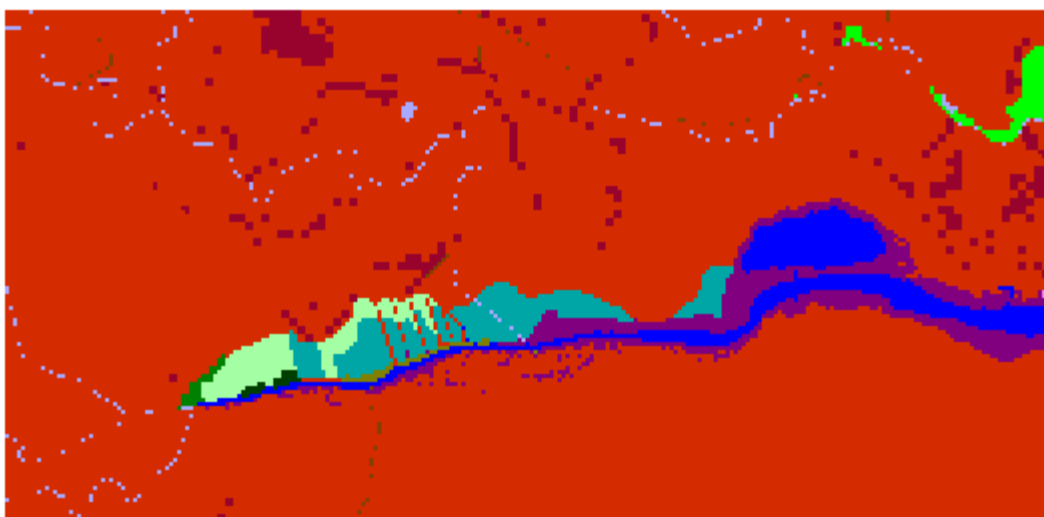
Huleia Context, 2075, 1.5 meter



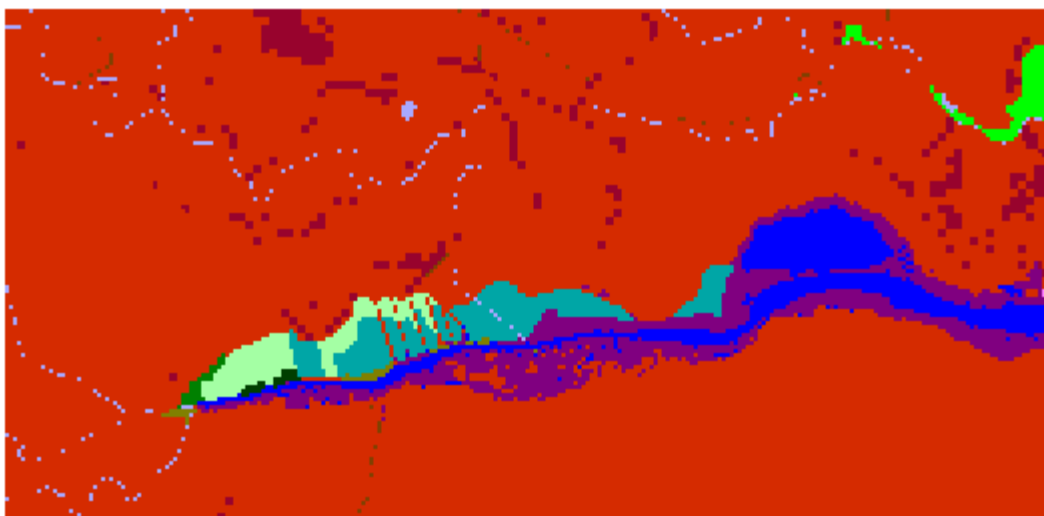
Huleia Context, 2100, 1.5 meter



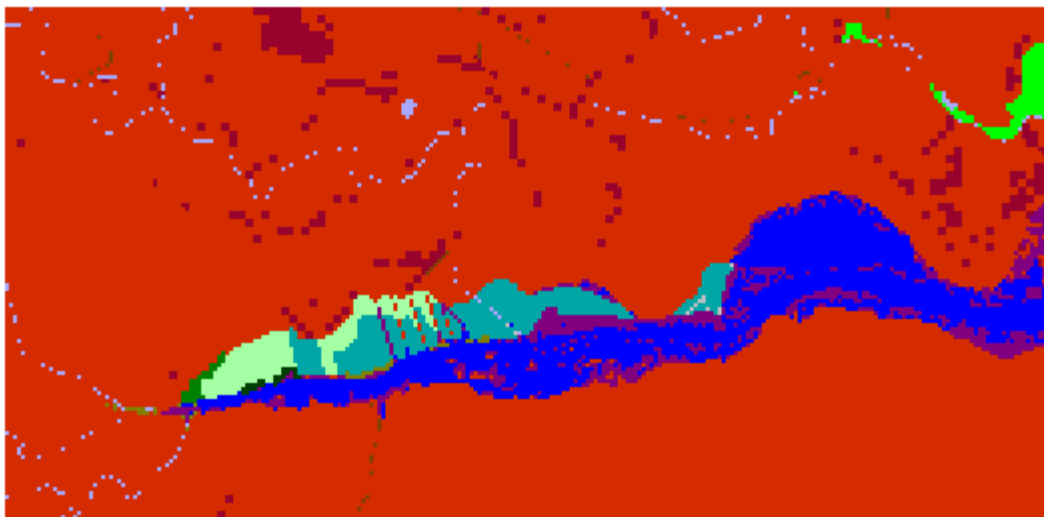
Huleia Context, Initial Condition



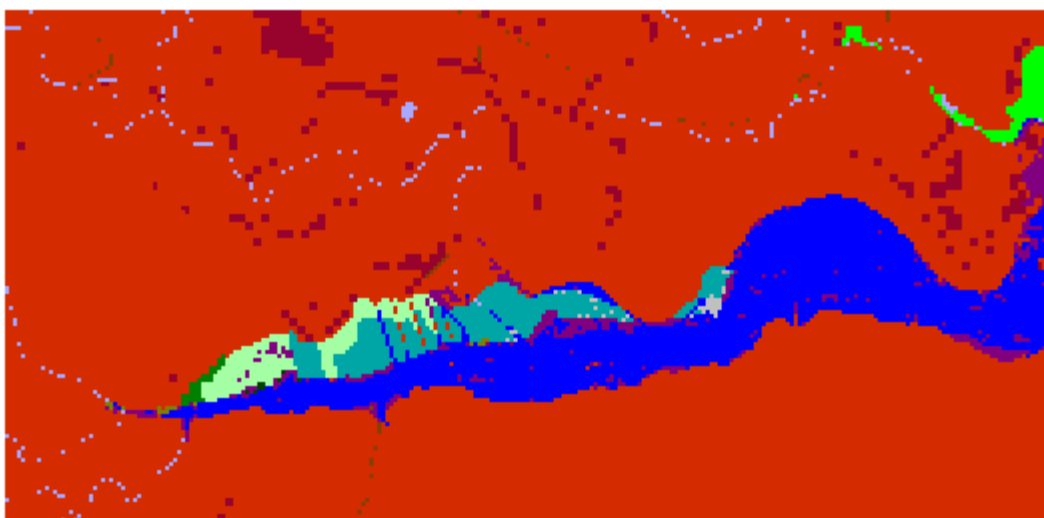
Huleia Context, 2025, 2 meter



Huleia Context, 2050, 2 meter



Huleia Context, 2075, 2 meter



Huleia Context, 2100, 2 meter